as inclusions in the brown glasses of samples 12033 (fines) and 12034 (breccia) designated as "KREEP" by HUBBARD *et al.* (1971). The amount of diaplectic glass in Apollo 12 soils is less than in Apollo 11 soil. Less than 1% of the grains of plagioclase composition in Apollo 12 soil are diaplectic glasses. Diaplectic plagioclase glass has also been found in the shocked basalt fragment 12057,14 (see below).

Clinopyroxene

Pyroxene with shock-induced lamellae as they have been described from Apollo 11 samples (ENGELHARDT *et al.*, 1970) occurs in Apollo 12 soil, breccias, and fragments of shocked basalt. Pyroxene grains with lamellae always show additional indications of mechanical deformation such as mosaic or undulatory extinction and irregular fractures or cleavages. Some grains contain only a few thin lamellae. More strongly shocked grains show many closely spaced lamellae. Most grains contain only one lamellae set. Rarely two lamellae systems cross each other at angles not far from 90°. In general, the lamellae do not extend through the whole grain, but prefer limited areas. Because these areas are often bounded by fractures it seems likely that brittle fracturing preceded lamellae formation. Bending of lamellae may indicate gliding parallel to lamellae planes.

We have measured the orientation of pyroxene lamellae against the optical directions n_x, n_y, n_z (Fig. 1). Some of the lamellae within the zone n_x–n_z may be parallel to (001) corresponding to lamellae known from shock experiments (SCLAR, 1970, HORNEMANN and MÜLLER, 1971); nuclear explosions (SHORT, 1969, JAMES, 1969); and the Ries crater (STÖFFLER, unpublished data). Lamellae of very irregular orientations which we have found in the majority of shocked pyroxene grains seem to be typical for shock deformation. Similar orientations have been found by HORNEMANN and MÜLLER (1971) in pyroxene, shock-loaded at pressures from below 100 up to 390 kbars. In accordance with these experiments, pyroxene with lamellae occurs in shocked basalt fragments together with still birefringent plagioclase. The lowest peak pressure for lamellae formation must be appreciably lower than the pressure which produces diaplectic plagioclase glass.

In Apollo 12 soils and breccias investigated by us, the amount of pyroxene grains

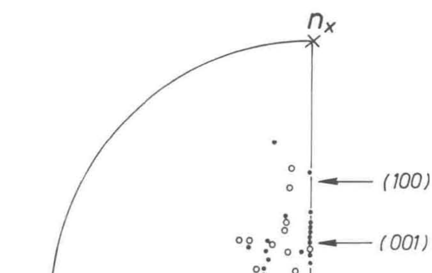

Fig. 1. Orientation of shock lamellae in clinopyroxene. Open circles, Apollo 11; dots, Apollo 12.

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Shock metamorphism and origin of regolith and breccias at the Apollo 11 and Apollo 12 landing sites

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Abstract—Shock-induced fracturing, mosaicism, and planar deformation structures in plagioclase, clinopyroxene, ilmenite, and tridymite, and diaplectic plagioclase glass have been observed in soils, breccias, and crystalline rocks. Shocked crystalline rocks can be classified into 5 stages of progressive shock metamorphism.

Glasses produced by shock melting of minerals and rocks have been classified into 6 morphological types. From the chemical composition five main groups of glasses are derived which originate from following parent rock types: mare basalts, basaltic differentiates of the "KREEP"-type, anorthositic, and pyroxenitic rocks.

Based on grain size, and modal and chemical composition, the regolith is interpreted as the product of repeated impacts which mixed rocks and minerals of a dominantly local origin together with shock fused glasses from local and farther distant sources.

Breccia modes show close relationships to the modes of adjacent soil. Some breccias containing unshocked, shocked, and shock-melted crystalline rocks of rather uniform composition are products of large impacts penetrating into the crystalline basement. The majority of breccias were formed by smaller impacts affecting only the regolith. They are consolidated by various amounts of shock-melted soil formed by the increased heat production characteristic of shock compression of porous materials. Of these breccias five types are distinguished which are based on differences in texture, matrix glass, and content of shocked minerals.

INTRODUCTION

OBJECTIVES OF THE present paper are (1) detection and interpretation of shock effects in rocks and minerals, (2) chemical composition and origin of shock-fused glasses, (3) grain size distribution, modal composition, and impact origin of the regolith, and (4) modal composition, texture, and impact origin of breccias. Results of studies on Apollo 11 samples have been published in ENGELHARDT *et al.* (1970). This paper reports additional and new results on Apollo 11 and Apollo 12 materials.

From the following Apollo 12 samples single grains, grain mounts, and thin sections have been investigated: 12001,84 (< 1 mm), 12070,139 (< 1 mm), 12033,74 (1–2 mm), breccia 12034,11, breccia 12010,21, breccia 12010,4, basalt 12057,14, and basaltic vitrophyr 12009,31. Methods and apparatus used in this investigation have been described in ENGELHARDT *et al.* (1970).

SHOCK EFFECTS IN MINERALS

Plagioclase

Shock-induced lamellae of low refractive index and low or no birefringence (ENGELHARDT *et al.*, 1970; STÖFFLER, 1967) occur in single plagioclase grains of breccias and soils and in shocked basalt fragments. Small fragments of diaplectic plagioclase glass (ENGELHARDT *et al.*, 1970, footnote p. 370) occur in the regolith and *et al.*, 1970, p. 380) could be confirmed. According to this classification which is in general agreement with our classification proposed for terrestrial shocked rocks (STÖFFLER, 1966; ENGELHARDT and STÖFFLER, 1968; STÖFFLER, 1971), 5 stages of increasing shock metamorphism can be recognized in the fragments of lunar crystalline rocks based on well-defined shock effects in plagioclase and pyroxene and on the selective or complete shock fusion of rocks. The characteristics of stages 1 to 5 are described in some detail in a previous paper (ENGELHARDT *et al.*, 1970).

Shock pressures lower than those of stage 1 produce strong irregular fracturing of all rock constituents and mosaicism of plagioclase and pyroxene. Small fragments of basaltic rocks belonging to this stage of deformation are rather frequent in soil and breccias of Apollo 11 and Apollo 12.

Basaltic fragments of stages 1 and 2 are very rare, both in soil and breccias. Out of 79 basalt fragments > 0.25 mm of Apollo 11 soil (10085,25; 10085,26) only three fragments were found of stage 1 and three of stage 2. One small basalt fragment of stage 1 and one of stage 2 were found as inclusions in breccia fragments of Apollo 11 soil. No basalts of stages 1 and 2 were found among 58 basalt fragments > 0.25 mm from Apollo 12 soil (12033,74; 12070,139; 12001,89). Thin section 12057,14 of a basalt fragment provides interesting information about shock effects in lunar polycrystalline rocks. The modal composition (point counting) is 53 vol. % pyroxene, 38 vol. % plagioclase, 9 vol. % opaques, and a minor amount of tridymite. All pyroxene grains contain sets of equidistant shock lamellae, mostly within limited areas, which are often slightly bent. Most of the ilmenite grains show fine twin lamellae.

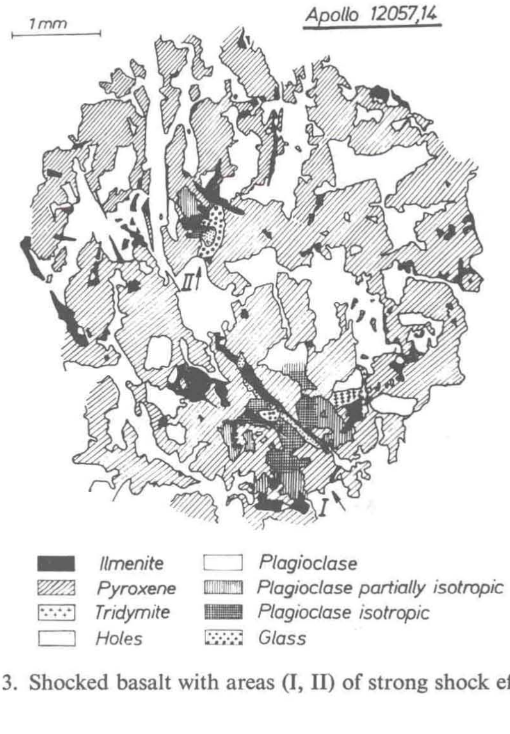

Fig. 3. Shocked basalt with areas (I, II) of strong shock effects.

with lamellae is lower than in Apollo 11 soils and breccias. In Apollo 12 soils 12070 and 12001 less than 1% of all pyroxene fragments contain lamellae.

Olivine

No shock effects have been observed by optical microscopy and by X-ray analysis in the Apollo 12 samples available for our studies. Transmission electron micrographs were obtained from shocked olivine grains from Apollo 11 described in ENGELHARDT *et al.* (1970). Dislocations in (010) with the Burgers vector parallel to [001], characterized by long screw components have been observed (Fig. 2). Wavy dislocations predominantly parallel to [010] have been found in particles with (001) approximately perpendicular to the electron beam. The dislocation density has been estimated to 10^{10}–10^{11} per cm^2.

Transmission electron micrographs of some olivine particles from soil 12070,139 revealed screw dislocations with the Burgers vector parallel to [001]. They may be of shock origin.

Ilmenite

Deformational twin lamellae occur in shocked basalt fragments containing pyroxene with shock lamellae. They obviously form at similar or lower shock pressures than those required for the formation of pyroxene lamellae.

Tridymite

Planar features parallel to a hexagonal prism have been observed in tridymite adjacent to diaplectic plagioclase glass in the basalt fragment 12057,14 (see below). It may be that they were produced by shock.

SHOCK METAMORPHISM OF CRYSTALLINE ROCKS

From the observed shock effects in Apollo 12 samples the previously established classification of progressive shock metamorphism of Apollo 11 rocks (ENGELHARDT

Fig. 2. Dislocations in shocked olivine from Apollo 11 (10085,26). Transmission electron micrograph. Dark field image produced by a reflection $\vec{g}$ = 002. Particle normal near [010]. Acceleration voltage 100 kV. (Siemens Elmiscope 101.)

Morphological types

According to morphology and texture the shock-fused polymineralic glasses may be classified into the following groups: *angular fragments* occur in soils as well as in breccias and range in size from less than 1 μm up to several mm (see Tables 6 and 7). *Regular forms of revolution* are minor constituents of soils and breccias, ranging in shape from spherules to ellipsoids, cylinders, dumbbells, and teardrops. We observed such bodies in the size fractions between 0.3 μm and about 2 mm. They are twice as abundant in Apollo 11 than in Apollo 12 samples (see Tables 6, 7, and 8).

Angular fragments and regular bodies are either homogeneous or heterogeneous. The latter show flow structures, schlieren, vesicles, and inclusions of unshocked or shocked mineral and rock fragments. They have a wide range of colors (colorless, green, yellow, orange, brown, red, violet, nearly opaque) and refractive indices which increase with increasing $FeO + TiO_2$ (Fig. 4) and decreasing $SiO_2 + Al_2O_3$. The majority of fragments and regular bodies contain minute metallic spherules or minute euhedral opaque crystals. Both types of glasses are sometimes partly or completely devitrified. Apollo 12 glasses show distinctly higher degrees of devitrification than Apollo 11 glasses.

In Apollo 12 samples glass fragments and few regular bodies of a characteristic beige-brown to maroon-brown color occur which were not found in Apollo 11 soils and breccias. These glasses show flow structures and are commonly rich in schlieren, vesicles, and mineral inclusions which are mostly shocked. All of them contain devitrification products, some of which were formed in the immobile matrix, mostly as spherulites, others at higher temperatures within the flowing melt. Most typical of the latter are small lath-like microlites with skeletal terminations, arranged in flow lines.

Glassy agglomerates are major constituents of soils and breccias. Their shapes are very irregular, mostly similar to slags or cinders. They consist of highly vesiculated glass, including and cementing together mineral and rock fragments. The glass is of yellow to dark brown color and commonly contains abundant minute metallic spherules. It is similar to the glassy coatings and the matrix glass of breccias. Distinction between glassy agglomerates and angular glass fragments becomes increasingly

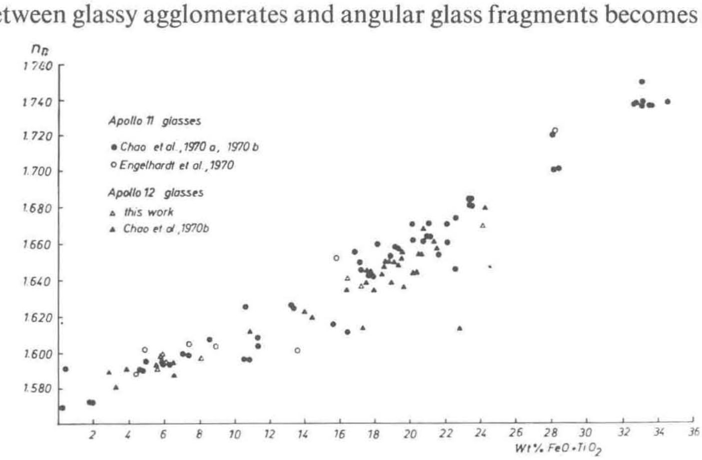

Fig. 4. Apollo 11 and Apollo 12 glasses: Refractive index versus $FeO + TiO_2$ content.

Table 1. Composition of glasses formed by local fusion in shocked basalt 12057,14.

	(1)		(2)		(3)	
SiO_2	45.94		47.92		30.79	
TiO_2	1.08		1.60		16.52	
Al_2O_3	0.93		12.99		5.51	
FeO	36.67		22.05		34.61	
MgO	2.83		2.35		0.26	
MnO	0.41		0.25		0.28	
CaO	10.06		11.73		7.68	
Na_2O	0.00		0.10		0.18	
K_2O	0.00		0.25		0.35	
Total	97.92		98.24		96.18	
CIPW norm						
quartz	0.19		4.05		0.18	
orthoclase	0.00	2.73	0.59	41.74	2.07	16.96
albite	0.00		4.15		1.52	
anorthite	2.54		32.95		13.19	
diopside	41.59		22.03		22.15	
enstatite	4.95	93.15	4.33	54.70	0.44	47.84
ferrosilite	46.61		28.34		25.25	
ilmenite	2.05		3.04		31.38	

(1) Greenish-brown glass, shock area I; (2) Green glass, shock area II; (3) Dark brown glass, shock area III.

Within three small areas (I, II, III), about 1 mm^2 each, local stress concentrations resulted in stronger shock effects (Fig. 3). In the center of these areas local fusion produced glasses the compositions of which are shown in Table 1. None of these glasses corresponds to the bulk composition of the rock. Area I shows concentric zones of diminishing pressure (decreasing shock metamorphism) around the central melt; the innermost zone contains diaplectic plagioclase glass. In an outer zone the plagioclase is partially isotropic (lamellae parallel to (010) and irregular isotropization), and passes gradually into birefringent plagioclase. Tridymite grains within this zone show planar features parallel to a hexagonal prism. Diaplectic plagioclase glass and partially isotropic plagioclase occur also around the central melts of areas II and III.

All three areas of high stress concentrations are situated adjacent to large ilmenite crystals. Apparently, shock waves of high peak pressures were produced by reflection at the grain boundaries of ilmenite which has the highest impedance of all constituents.

Glasses Produced by Shock Melting

The most conspicuous constituents of Apollo 11 and Apollo 12 soils and breccias are glasses of various morphology, color, and composition. A minor amount of glasses is of volcanic origin. They contain euhedral phenocrysts of olivine and other minerals, and they shall not be considered here. The majority of glasses are produced by shock. Most of them are of polymineralic composition. Monomineralic glasses are almost exclusively represented by diaplectic plagioclase glasses formed in the solid state. Monomineralic glasses formed by shock fusion are extremely rare.

Table 3. Electron microprobe analyses of colored glasses of basaltic composition from Apollo 12 (wt. %).

	1	2	3	4	5	6	7	8	9	10
SiO_2	48.24	43.22	48.20	48.00	48.58	41.77	48.09	45.22	47.09	45.17
TiO_2	2.44	3.26	2.46	2.95	2.44	3.30	2.45	4.68	2.93	2.95
Al_2O_3	15.11	10.83	14.42	14.16	14.85	10.47	15.29	9.78	15.16	15.65
FeO	11.69	19.59	11.98	12.71	11.94	20.35	10.85	21.22	11.59	13.43
MnO	0.18	0.19	0.16	0.15	0.18	0.16	0.14	0.22	0.15	0.10
MgO	9.15	9.57	9.25	9.04	9.08	10.11	10.19	7.94	9.38	7.61
CaO	10.31	9.70	9.85	10.01	10.00	9.60	9.78	10.81	10.38	12.12
Na_2O	0.72	0.21	0.75	0.62	0.76	0.23	0.78	0.26	0.70	0.92
K_2O	0.56	0.00	0.57	0.46	0.55	0.02	0.57	0.03	0.56	0.34
ZrO_2	0.13	—	0.15	0.13	0.13	—	0.12	0.04	0.14	—
Cr_2O_3	—	—	—	—	—	—	—	—	—	—
BaO	0.09	—	0.10	0.08	0.09	—	0.06	0.03	0.08	—
Total	98.63	96.57	97.88	98.33	98.60	96.02	98.32	100.23	98.18	98.29
Color	Y	YB	GY	Y	Y	YB	RB	VB	Y	B
Sample	12010,4	12010,4	12010,4	12010,4	12010,4	12010,4	12010,4	12010,4	12010,4	12070,139
No.	K12	K13	K15A	K17	K18	K20	K27	K29	K40	208

Table 3 (continued)

11	12	13	14	15	16*	17*	18*	19*	20*
43.13	46.13	48.08	45.65	46.51	48.76	49.18	47.84	41.13	46.69
5.35	1.23	3.36	3.22	2.83	2.00	2.57	2.37	3.49	2.86
10.05	19.61	12.72	9.20	11.71	13.99	14.53	14.40	11.97	4.36
18.78	6.81	17.17	19.39	15.79	12.95	13.00	13.64	19.31	15.43
0.18	0.07	0.17	0.17	0.14	0.09	0.15	0.15	0.23	0.19
6.06	8.47	5.54	9.46	9.41	10.50	8.24	8.21	9.26	12.62
10.85	12.83	11.55	10.63	10.21	10.36	10.21	10.31	11.60	14.85
0.11	0.68	0.74	0.15	0.18	0.45	0.70	0.41	0.03	0.14
0.03	0.36	0.00	0.37	0.19	0.22	0.62	0.29	0.00	0.00
—	—	0.01	0.01	—	—	—	0.09	0.01	—
—	—	0.23	0.41	—	—	—	—	—	—
—	—	0.02	0.12	—	—	—	0.07	0.04	—
94.53	96.19	99.60	98.83	96.97	99.32	99.21	97.80	97.08	97.14
YB	Be	B	B	O	GY	Y	GY	Y	YB
12001,84	12070,139	12033,74	12033,74	12070,139	12010,4	12010,4	12010,4	12010,4	12010,4
212	213	193.13	193.15	167K1	K9	K11	K14	K34	K37

Color code: B—Brown; Be—Beige; G—Greenish; O—Olive green; R—Red; V—Violet; Y—Yellow.
* Regular forms of revolution.

Refractive indices of 3 glasses (microprobe analysis number is parenthesized): 1.641(10); 1.669(11); 1.597(12).

difficult and finally impossible with decreasing grain size. In coarser size fractions agglomerates are similar to glass coated breccia fragments and exactly distinguishable from them only in thin sections.

Glassy coating of rocks. Some fragments of breccias, basàltic rocks, and minerals are partly or completely covered by a brown glass containing vesicles, schlieren, fragmental inclusions, and very often, metallic spherules. Glass coated breccias and glassy agglomerates are difficult to distinguish without thin sections.

Glassy matrix of breccias. Brownish glass was observed as an important constituent of the fine-grained matrix of many Apollo 11 and Apollo 12 breccias. As far as can be judged from microscopic observation this glass consists mostly of minute irregular particles. Some matrix glass has a vesiculated appearance.

Glass lining small impact craters. Pit craters in the millimeter and submillimeter range on rock surfaces are lined with thin glass coatings formed by shock melting of the target rock (HÖRZ *et al.*, 1971; CHAO *et al.*, 1970b; NEUKUM *et al.*, 1970).

Chemical types

Chemical compositions of 38 Apollo 11 glasses and 62 Apollo 12 glasses have been determined by microprobe analysis. Results for Apollo 11 glasses have been previously published (ENGELHARDT *et al.*, 1970). Results for Apollo 12 glasses are given in Tables 2 to 4. On the basis of chemical composition the investigated shock produced glasses may be divided into five main types: (1) Colorless diaplectic glasses of feldspar composition (plagioclase and alkalifeldspar) (ENGELHARDT *et al.*, 1970, p. 371). (2) Colorless to pale green glasses of "anorthositic" composition (Table 2). (3) Colored glasses of fairly variable "basaltic" composition (Table 3). (4) Maroon-brown glasses ("KREEP"-type) (Table 4). (5) Red-brown to black glasses of "pyroxenitic" composition (ENGELHARDT *et al.*, 1970, Table 4).

Table 2. Electron microprobe analyses of colorless (25–30) and pale-green (31–34) glasses of anorthositic composition from Apollo 12 (wt. %).

	25	26	27	28	29	30*	31	32	33	34
SiO_2	52.10	45.66	50.33	49.18	50.65	44.66	43.25	44.02	44.01	43.21
TiO_2	0.51	0.50	0.53	0.82	2.93	0.91	0.28	0.30	0.26	0.29
Al_2O_3	16.60	24.36	15.80	13.37	17.25	26.85	23.94	24.06	24.82	24.66
FeO	9.76	8.09	11.08	13.37	11.64	5.26	5.48	5.55	5.78	5.28
MnO	0.09	0.08	0.11	0.15	0.13	0.08	0.06	0.07	0.03	0.07
MgO	9.16	4.87	9.28	9.80	9.50	5.29	8.58	8.48	7.82	7.63
CaO	10.53	14.77	10.71	9.46	10.45	14.60	15.39	15.43	15.71	15.86
Na_2O	0.36	0.29	0.10	0.51	0.76	0.98	0.05	0.17	0.09	0.12
K_2O	0.08	0.06	0.00	0.19	0.58	0.22	0.00	0.00	0.00	0.00
ZrO_2	—	—	0.02	0.02	0.04	—	—	—	—	—
Cr_2O_3	—	—	—	—	—	—	—	—	—	—
BaO	—	—	0.04	0.02	0.01	—	—	—	—	—
TOTAL	99.19	98.69	98.01	96.90	103.94	98.85	96.99	98.04	98.53	97.08
Sample	12010,4	12010,4	12010,4	12010,4	12010,4	12010,4	12001,84	12001,84	12070, 139	12070, 139
No.	K16	K23	K28	K36	K39	K44	207	215	216	217

* Regular form of revolution.

Refractive indices of 4 glasses (microprobe analysis number is parenthesized): 1.597(31); 1.598(32); 1.59(33); 1.590(34).

Although some overlap occurs, these groups are principal compositional types characterized by differences in the abundances of major and minor elements (Figs. 5 to 8), CIPW-norms (Fig. 9), and colors. The glasses of "anorthositic" composition have high Al and low Ti, Fe, and Mn contents. The basaltic glasses are lower in Al and higher in Ti, Fe, and Mn. "Basaltic" glasses from Apollo 12 are generally lower in Ti and generally higher in Si, in comparison with those from Apollo 11. The maroon-brown glasses described above, which we found only in Apollo 12 soils and breccias, are distinguished from the average of "basaltic" glasses by lower Mg contents (Fig. 6) and higher abundances of K, Ba, and Zr (Figs. 7 and 8). As reported by other investigators these glasses ("KREEP"-glasses) are additionally characterized by high contents in rare earths, P, and U (HUBBARD *et al.*, 1971). Red-brown to dark, mostly homogeneous glasses of "pyroxenitic" composition, characterized by extremely low contents in Al and the highest abundances of Ti, Mg, and Fe were found only in Apollo 11 soils and breccias (Figs. 5 and 6).

Origin of glasses

Main criteria for the shock origin of lunar glasses are the following: (1) shocked fragmental inclusions, (2) incorporation of minute Fe-Ni-spherules which may be an evidence for the material of the impacting body, (3) lack of euhedral phenocryst inclusions, (4) rareness of fragmental inclusions which show chemical reaction with the melt, (5) strong chemical heterogeneities within a small scale, (6) existence of shock zones beneath glassy crusts of rocks, indicating hypervelocity impact of splashed melts, and (7) direct evidence of localized shock fusion within crystalline rocks.

Most of the lunar glasses show one or more of these criteria of shock origin. The origin of some homogeneous glass particles is ambiguous because they do not contain

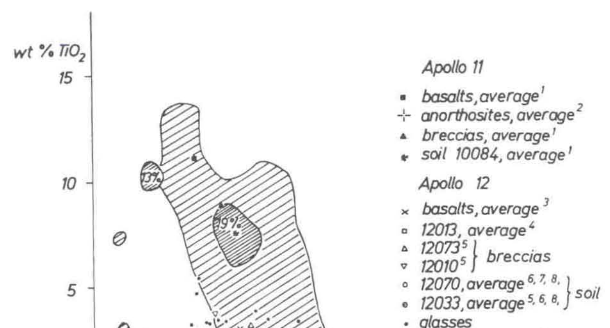

Fig. 5. TiO_2 versus Al_2O_3 contents of glasses, igneous rocks, breccias and soil from Apollo 11 and Apollo 12. Glass analyses of this work (Apollo 12) are represented by dots. All hatched areas comprise 222 data points of Apollo 11 glass analyses taken from LEVINSON, Vols. 1 and 2 (1970). The narrow-hatched areas comprise the indicated percentages of all data points. References for all other data are designated by superior numerals and listed in caption of Fig. 8.

Table 4. Electron microprobe analyses of maroon-brown glasses from Apollo 12 (wt. %).

	35	36	37	38	39	40	41	42	43	44
SiO_2	48.14	48.43	47.56	48.00	50.22	50.13	48.44	51.55	49.74	50.68
TiO_2	2.00	2.03	2.77	2.26	2.28	2.03	1.94	1.92	2.41	1.95
Al_2O_3	15.71	14.55	13.85	14.55	16.10	16.27	15.82	16.61	15.62	17.30
FeO	10.23	11.87	11.64	11.60	11.32	10.73	10.17	10.63	11.49	10.25
MnO	0.11	0.12	0.12	0.09	0.12	0.09	0.09	0.06	0.12	0.11
MgO	7.37	7.57	8.84	7.35	7.84	7.08	6.35	6.50	6.91	6.08
CaO	12.16	11.38	11.62	10.70	10.72	10.88	10.80	10.71	10.66	10.89
Na_2O	1.14	0.87	0.63	0.88	0.74	0.99	1.21	0.53	0.95	1.17
K_2O	0.44	0.67	0.82	0.65	0.99	0.50	0.31	1.54	0.35	0.55
ZrO_2	—	—	—	—	0.28	0.17	0.20	0.24	0.17	0.16
Cr_2O_3	—	—	—	—	0.20	0.17	0.18	0.14	0.18	0.16
BaO	—	—	—	—	0.14	0.11	0.14	0.13	0.13	0.12
TOTAL	97.29	97.50	97.85	96.07	100.75	99.15	95.65	100.56	98.73	99.42
Sample	12034, 11	12034, 11	12034, 11	12034, 11	12033, 74	12033, 74	12033, 74	12033, 74	12033, 74	12033, 74
No.	177K1	177K2	177K3	177K6	188.1	188.2	188.3	195.1	195.3	195.4

Table 4. (continued)

	45	46	47	48	49	50	51	52	53	54
SiO_2	49.17	49.02	49.40	49.24	49.38	50.08	48.91	50.70	49.77	50.42
TiO_2	2.33	2.33	2.06	2.76	1.87	2.16	2.32	2.25	2.08	2.07
Al_2O_3	16.26	15.59	16.23	15.26	15.64	16.50	16.11	15.51	17.47	15.75
FeO	10.70	11.54	10.67	11.29	11.57	10.80	11.95	10.52	10.13	10.53
MnO	0.08	0.06	0.07	0.11	0.12	0.06	0.12	0.10	0.10	0.09
MgO	7.80	8.01	7.27	6.82	8.36	7.05	7.15	5.73	6.65	6.85
CaO	10.87	10.68	10.72	10.80	10.89	11.33	11.11	11.23	11.00	10.99
Na_2O	1.03	0.47	0.50	1.07	0.86	0.97	0.99	1.05	1.03	0.95
K_2O	0.38	0.99	1.32	0.33	0.29	0.73	0.49	0.78	0.79	0.96
ZrO_2	0.12	0.23	0.29	0.15	0.16	0.14	0.16	0.14	0.14	0.14
Cr_2O_3	0.21	0.19	0.16	0.16	0.19	0.20	0.17	0.17	0.15	0.14
BaO	0.09	0.11	0.15	0.10	0.12	0.14	0.13	0.14	0.15	0.17
TOTAL	99.04	99.11	98.84	98.11	99.43	100.16	99.61	98.32	99.46	99.16
Sample	12033, 74	12033, 74	12033, 74	12033, 74	12033, 74	12033, 74	12033, 74	12033, 74	12033, 74	12033, 74
No.	195.5B	195.5G	195.6	195.7	193.1	193.2	193.3	193.4	193.5	193.6

Table 4. (continued)

	55	56	57	58	59	60	61	62*	63†	σ†	64††
SiO_2	49.55	49.07	49.19	47.32	49.80	47.49	48.91	46.42	49.17	1.24	48.4
TiO_2	2.04	2.46	0.24	3.32	2.52	3.81	2.29	3.41	2.27	0.64	1.60
Al_2O_3	16.66	15.47	15.63	19.66	15.74	15.53	16.54	16.67	16.02	1.05	16.9
FeO	10.60	11.45	11.94	9.51	11.66	12.60	10.88	10.32	11.02	0.71	11.6
MnO	0.12	0.11	0.10	0.09	0.10	0.12	0.07	0.09	0.10	0.02	0.15
MgO	7.78	6.69	8.45	7.25	6.81	7.26	7.84	8.43	7.28	0.81	9.8
CaO	11.04	10.55	10.93	11.91	11.01	11.21	10.45	12.89	11.07	0.63	10.4
Na_2O	1.12	1.00	0.44	0.90	1.00	0.97	0.38	0.41	0.87	0.24	0.90
K_2O	0.53	0.44	1.18	0.53	0.51	0.59	1.23	0.11	0.68	0.34	0.50
ZrO_2	0.13	0.16	0.17	0.11	0.17	0.13	—	—	0.17	0.05	0.09
Cr_2O_3	0.18	0.16	0.21	0.16	0.19	0.22	—	—	0.18	0.02	0.18
BaO	0.14	0.11	0.11	0.12	0.16	0.08	—	—	0.12	0.02	—
TOTAL	99.89	97.67	98.59	100.88	99.67	100.01	98.59	98.75	98.95		100.52
Sample	12033, 74	12033, 74	12033, 74	12033, 74	12033, 74	12033, 74	12001, 84	12034, 11			
No.	193.7	193.10	193.11	193.16	193.19	193.20	162K1	177K4			

* Regular form of revolution; † Average of analyses 35–62 and corresponding standard deviation; †† Analysis of norite from Apollo 12 by KEIL *et al.* (1971).

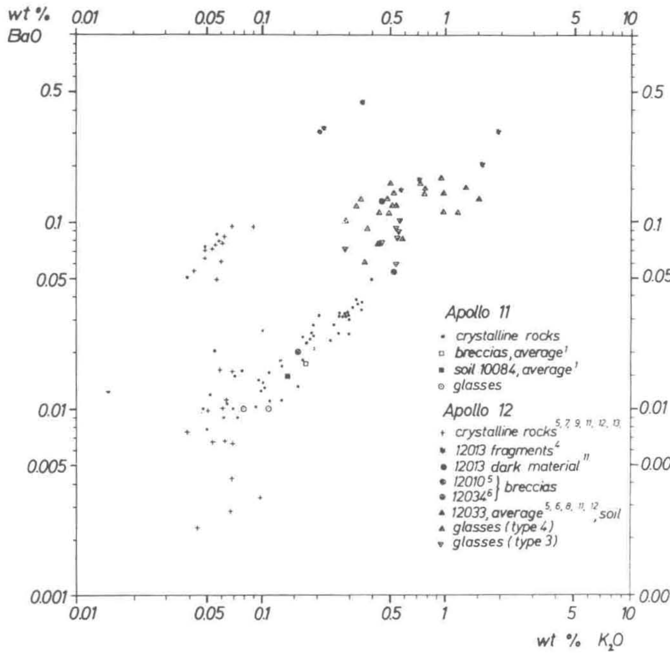

Fig. 7. BaO versus K_2O contents of glasses, igneous rocks, breccias and soil of Apollo 11 and Apollo 12. Glass analyses of this work are represented by triangles. Data of Apollo 11 glasses and crystalline rocks are taken from LEVINSON (1970) Vols. 1 and 2. References for all other data are designated by superior numerals and listed in caption of Fig. 8.

Therefore we conclude that a great number of glasses occurring in soils and breccias have not been produced by shock melting of basalts which are supposed to form the basement of the regolith at the landing sites. Source material of these glasses may be local soil and rocks from distant localities.

Discussing the nature of the source rocks of glasses attention has to be drawn to possible processes of local or selective melting in shocked crystalline rocks as they were observed in rock 12057,14. By such processes small glass particles of strongly different and aberrant compositions (Table 1) may be formed, which also may, to some extent, explain the broad scattering of points in the chemical composition plots. For this reason, one should be cautious in interpreting the compositional variability of basaltic glasses in terms of a discrete fractionation series of parent rocks.

Contrary to the broad variation in chemical composition of many angular fragments and regular bodies, the maroon-brown "KREEP"-glasses of Apollo 12 samples show a very narrow range of compositions (Table 4). In this respect and also by their morphology and texture, these glasses are similar to impact glasses from terrestrial suevites, such as the glass bombs of the Ries crater (ENGELHARDT, 1967). By their chemical composition the brown glasses may correspond to particular norites rich in K, P, and Zr analyzed by KEIL *et al.* (1971) and WOOD *et al.* (1971). The provenance of these glasses is discussed in the next sections.

direct shock evidence. Some of the very homogeneous regular glass bodies may have been formed by condensation from shock-produced silicate vapor.

Angular fragments and regularly shaped lunar glasses are considered to be cataclastic particles of quenched melts produced by impacts. They show a considerable variation of chemical composition which may be due to large scale impact melting of different parent rocks and/or to fusion of small volumes of rock or soil caused by small impacts. It may be concluded from the clustering of points in the plots in Figs. 5, 6, and 9 that main parent crystalline rocks were of "basaltic," "anorthositic," and "pyroxenitic" composition.

Most of the "basaltic" glasses of Apollo 11 and Apollo 12 are similar in composition to the soils but different from the large basaltic fragments (Figs. 5, 6, and 9).

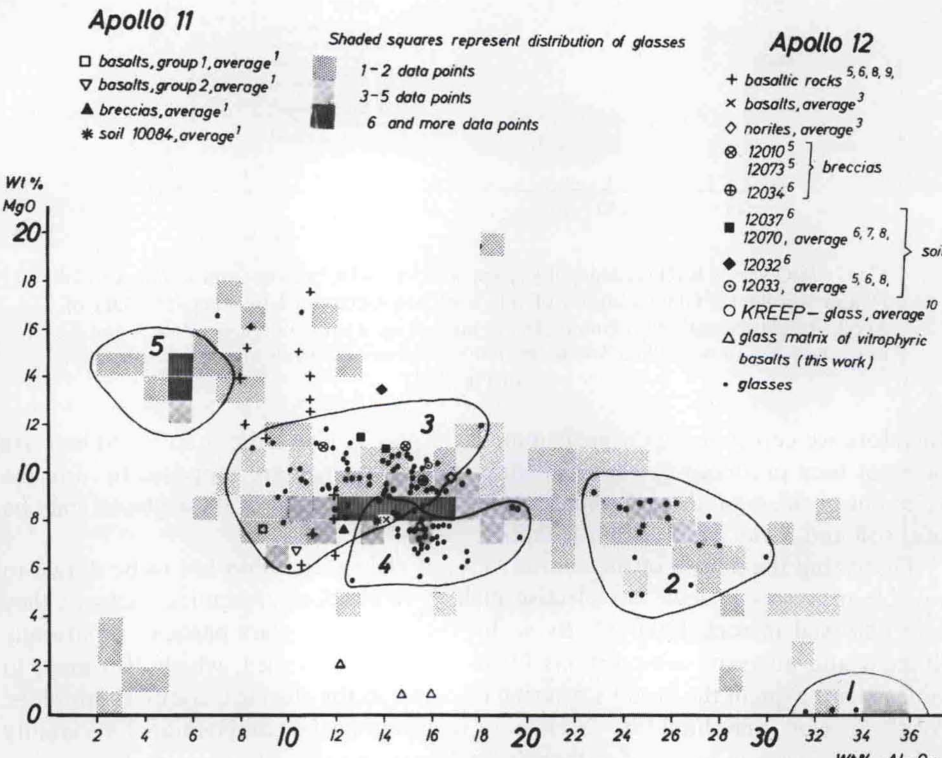

Fig. 6. MgO versus Al_2O_3 contents of glasses, igneous rocks, breccias and soil from Apollo 11 and Apollo 12. The data of Apollo 12 glasses of the present work together with the data of AGRELL *et al.* (1971), CHAO *et al.* (1970b), and KEIL *et al.* (1971) are represented by dots. Shaded areas represent the distribution of 222 data points of Apollo 11 glasses taken from LEVINSON (1970), Vols. 1 and 2. References for all other data are designated by superior numerals and listed in caption of Fig. 8. Area 1 = diaplectic plagioclase glasses; area 2 = "anorthositic" glasses; area 3 = "basaltic" glasses of Apollo 12; area 4 = maroon-brown ("KREEP") glasses of Apollo 12; area 5 = red-brown ("pyroxenitic") glasses of Apollo 11.

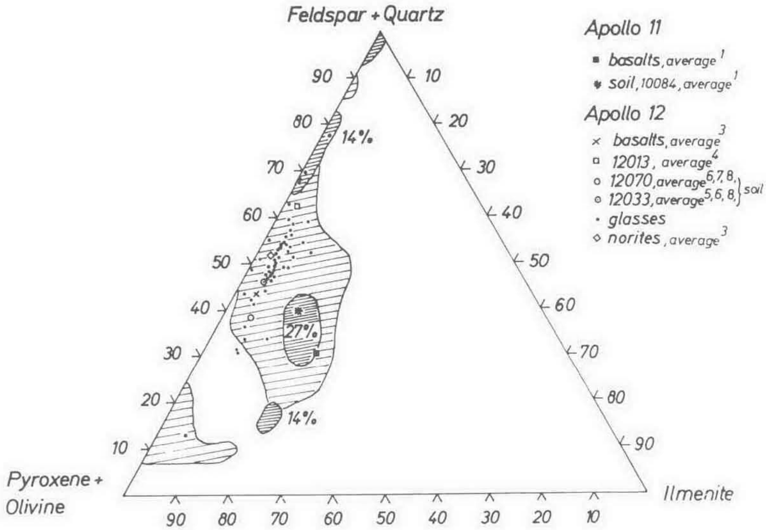

Fig. 9. CIPW norms of glasses, igneous rocks, breccias, and soil of Apollo 11 and Apollo 12. Glass analyses of this work (Apollo 12) are represented by dots. All hatched areas comprise 222 data points of Apollo 11 glass analyses taken from LEVINSON, Vols. 1 and 2 (1970). The narrow-hatched areas comprise the indicated percentage of all data points. References for all other data are designated by superior numerals and listed in caption of Fig. 8.

Modal compositions of individual size fractions, determined by optical microscopy, below 250 μm in loose grain mounts, above 250 μm in thin sections of grain mounts, and calculated overall compositions are given in Tables 6 to 8 and Figs. 10 and 11. X-ray examination of the fractions < 10 μm of 10084,106 and < 20 μm of 12001,84 and 12070,139 revealed the presence of pyroxene, plagioclase, ilmenite, cristobalite, metallic iron, and troilite.

Table 6. Modal composition of grain size fractions of Apollo 11 soil (10084,106).

	10–20 μm	20–63 μm	63–125 μm	125–250 μm
Basalt	—	—	4.5	19
Anorthosite	—	—	—	1.5
Breccia	—	—	} 45[3]	} 54[4]
Agglomerates	—[1]	—[1]		
Glass fragments, dark	23	31	4.1	4.4
Glass fragments, light	11	5.1	2.8	3.1
Regular glass bodies	4.0	1.0	1.1	1.3
Pyroxene + olivine	30	35	31	12
Plagioclase	22	19	8.6	2.4
Opaques	10[2]	9.2[2]	2.0	2.4
Pyroxene/plagioclase	1.4	1.8	3.6	5.0

[1] Some agglomerates included in "opaques"; [2] Including some agglomerates; [3] Breccia ≈ 11%, agglomerates ≈ 34%; [4] Breccia ≈ 24%, agglomerates ≈ 30%.

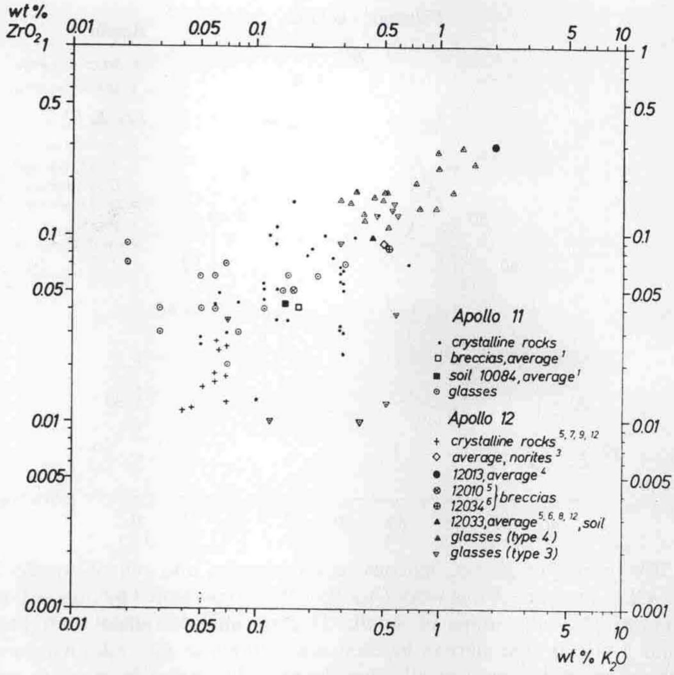

Fig. 8. ZrO_2 versus K_2O contents of glasses, igneous rocks, breccias, and soil from Apollo 11 and Apollo 12. Glass analyses of this work are represented by triangles. Data of Apollo 11 glasses and crystalline rocks are taken from LEVINSON (1970), Vols. 1 and 2. References for all other data are designated by superior numerals and are as follows: [1]COMPSTON *et al.* (1970); [2]WOOD (1970); [3]KEIL *et al.* (1971); [4]WAKITA and SCHMITT (1970); [5]LSPET (1970); [6]WAKITA *et al.* (1971); [7]ANNELL *et al.* (1971); [8]ROSE *et al.* (1971); [9]SMALES (1971); [10]MEYER *et al.* (1971); [11]HUBBARD *et al.* (1971); [12]BROWN *et al.* (1971); [13]BRUNFELT *et al.* (1971).

REGOLITH

The grain size distribution (dry sieving) of Apollo 12 soils 12001,84 and 12070,139, both collected near LM site (SUTTON and SCHABER, 1971), are given in Table 5. The two Apollo 12 soils show nearly identical size distributions, very similar to Apollo 11 soil (ENGELHARDT *et al.*, 1970). Medium diameter is 54 μm for Apollo 12 soils and 48 μm for Apollo 11 soil. On a log-probability plot both size distributions appear slightly bimodal.

Table 5. Grain size distribution of Apollo 12 soils (dry sieving; wt. %).

μm	12001,84	12070,139	Average
1000–500	3.3	3.7	3.5
500–250	7.8	9.1	8.4
250–125	14.6	15.5	15.0
125– 63	20.4	17.8	19.1
63– 20	28.9	28.0	28.4
< 20	25.0	25.9	25.4

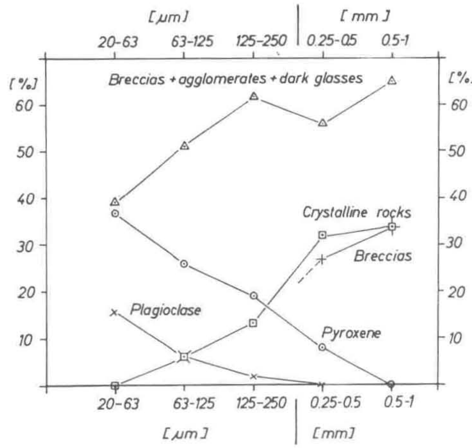

Fig. 11. Modal composition of grain size fractions of Apollo 12 soil (average of 12001,84 and 12070,139).

mineral grains. The ratio (pyroxene + olivine)/plagioclase diminishes with decreasing size, probably due to the larger size of pyroxene in the average source rocks. Olivine is a minor constituent. Taking into account the increase of plagioclase in the finest fractions the ratio (pyroxene + olivine)/plagioclase may be a little less than 2.0 for the Apollo 11 soil and a little less than 3.6 for Apollo 12 soils 12001 and 12070.

The average of 14 basaltic rocks from Apollo 11 (COMPSTON *et al.*, 1970) gives a normative ratio of pyroxene/plagioclase of 1.63, in fairly good agreement with the modal ratio of Apollo 11 soil. We conclude, therefore, that the clastic components of this soil were essentially produced by disintegration of local basaltic rocks forming the basement of the regolith. Nine analyses of Apollo 12 basalts published by LSPET (1970) give an average (pyroxene + olivine)/plagioclase ratio of 1.96. Twenty-eight analyses of basaltic fragments from Apollo 12 made by KEIL *et al.* (1971) result in an average ratio of 1.23. Both ratios are appreciably lower than the modal ratio found in Apollo 12 soil. We conclude that the clastic components of the soil at the Apollo 12 site were produced from rocks richer in pyroxene than those which occur as larger fragments at the surface.

Most of the glasses forming the second group of soil constituents are glassy agglomerates. We assume that they were formed by splashes of a low viscosity melt which met the soil surface at low velocities, incorporating and agglutinating solid soil particles. The melt was ejected from young primary or secondary impact craters, not far from both landing sites, because shape and fragility of the agglomerates exclude any reworking and transportation over long distances. Some agglomerates may have a different origin, as discussed in the next section.

Splashes of shock-produced melt formed glass coatings on larger rocks and on small rock and mineral fragments. Glass-coated breccia fragments are much more frequent than coated fragments of crystalline rocks. This fact possibly reflects the composition of the uppermost layer of the regolith when it was hit by melt splashes.

Table 7. Modal composition of grain size fractions of Apollo 12 soils (12070 and 12001).

	20–63 μm			63–125 μm			125–250 μm			250–500 μm	500–1000 μm
	70	1	Av.	70	1	Av.	70	1	Av.	Av.	Av.
Basalt	—	—	—	4.6	4.6	4.6	8.0	11	9.5	32	28
Anorthosite	—	—	—	1.2	2.2	1.6	3.1	3.8	3.9	—	6
Breccia	—	—	—	} 50	} 46	} 48	} 59	} 56	} 58[1]	} 27	34
Agglomerates	—	—	—							} 29	31
Glass fragments, dark	41	38	39	7.1	3.6	5.3	3.1	7.2	5.1	}	—
Glass fragments, light	7.7	8.3	8.0	3.8	4.5	4.2	2.2	1.2	1.7	3	1
Regular glass bodies	0.7	1.7	1.2	0.3	1.5	0.9	0.7	0.5	0.6	—	—
Pyroxene + olivine	37	36.	37	24	28	26	22	17	19	8	—
Plagioclase	11	12	11	4.7	7.9	6.3	1.5	2.4	1.9	—	—
Opaques	2.7	4.7	3.7	4.2	1.1	2.6	0.9	1.4	1.2	—	—
Pyroxene/plagioclase	3.4	3.0	3.4	5.1	3.6	4.1	15	7.1	10.0	—	—

[1] Breccia ≈ 10%. Agglomerates ≈ 48%.

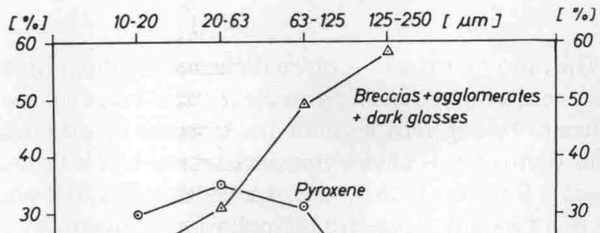

Fig. 10. Modal composition of grain size fractions of Apollo 11 soil (10084,106).

The modal compositions of the two Apollo 12 soils are nearly identical and very similar to that of the Apollo 11 soil. Differences are the higher (pyroxene + olivine)/plagioclase ratio, the higher amount of glass fragments, the slightly higher ratio of dark glasses to light glasses, and the lower content of regular glass bodies in the Apollo 12 soils. The higher content of crystalline rocks in Apollo 12 soils (Table 8) is mainly due to the fact that the modal composition of the rock rich fractions > 250 μm of Apollo 11 soil has not been determined.

Lunar soils consist of three groups of constituents: (1) fragments of minerals and rocks, produced by mechanical disintegration; (2) glasses produced by shock melting, mixed with fragmental material and in part mechanically disintegrated; (3) meteoritic material. Of group (1), rock fragments (basalts, breccias, anorthositic rocks) prevail in size fractions > 100 μm. Below 100 μm, rock fragments are replaced by single

Meteoritic material, though very subordinate, is enriched within the finest fractions of the regolith in which the metallic iron and troilite content is high enough to be detected by X-ray diffraction.

The modal composition of the 1–2 mm fraction of soil 12033,74, collected at the north rim of Head Crater, is 70 vol. % maroon-brown glass, 15 vol. % breccias, 14 vol. % basalts, and 1 vol. % pyroxene. Although neither the coarse fines of 12070 and 12001 nor the fine fines of 12033 could be investigated, it is obvious that the light-colored soil near Head Crater has a composition quite different from that of the dark soil near the LM (Table 8). We assume that the maroon-brown glasses which are the main constituents of 12033,74 are products of one single impact, possibly within the Fra Mauro formation (see next section).

In conclusion, the soil at Apollo 11 and Apollo 12 landing sites is the product of repeated impacts on the lunar surface which mixed disintegrated rocks and fractured minerals of a dominantly local origin together with shock-fused glasses from local and farther distant sources. In Apollo 11 and Apollo 12 soil components which obviously do not originate from mare rocks are anorthositic rock and glass fragments, probably derived from impacts in terra areas, and in Apollo 12 soils rock fragments and maroon-brown glasses which may be derived from rocks underlying the mare basalts (Fra Mauro formation).

Unlike terrestrial impact formations like the Ries suevite, the lunar regolith contains a large amount of shock-induced fusion products but only very few rock and mineral fragments with clear indications of shock. Two reasons may be responsible for this difference between regolith and terrestrial suevites: (1) Impacts into loose and porous material produce more irreversible heat and consequently more molten material than impacts on solid rocks (see below). (2) In contrast to terrestrial suevites which are products of one single event, the lunar regolith was formed by multiple impacts. Each of them produced a certain amount of vapor, melt, and shock-deformed minerals and rocks, diluted by a much larger mass of fractured material. From an estimate by GAULT (1970), less than 1% of the displaced mass of each impact is vaporized and fused. Later impacts into older impact debris would increase the ratio of shock fused glass. Hence, the glass content of the regolith should have kept growing through its long history of several billion of years. The unlimited continuation of this process, without later addition of undamaged primary rocks, should finally result in the conversion of the whole detritus into glass, the final product of shock metamorphism.

BRECCIAS

Modal compositions of 4 breccias from Apollo 11 and of two breccias from Apollo 12 have been determined by point counting of thin sections. The results are given in Table 10. Matrix includes all material not resolvable with the microscope, i.e., glassy cement and very fine fragments. To some extent variable section thicknesses may influence the measured amounts of matrix.

Modal compositions of breccias and soils from the same localities are similar (Tables 8 and 10) if allowance is made for the fact that the determinations of modal compositions of soils refer to smaller grain sizes than those of breccias. The higher

Contrary to the agglomerate forming melt splashes, regular glass bodies were embedded as solid bodies into the soil. Most likely, most of them were formed by the breakup of impact-induced liquid jets. Some of the angular glass fragments are disintegrated agglomerates. Others are fragments of quenched shock melts transported from distant localities and reworked by repeated impacts.

It has been shown by chemical analyses that the glassy components of the soils are substantially different from the local basaltic rocks at both landing sites. This is also confirmed by a comparison between modal and normative compositions of the soils (Tables 8 and 9). In both soils the normative (pyroxene + olivine)/plagioclase ratio is lower than the modal ratio as determined from the mineral frequencies. We conclude that the glass components of both soils are richer in normative plagioclase than the fragmental mineral components.

Table 8. Modal composition of Apollo 11 and Apollo 12 soils.

	Apollo 11 10084,106 10–250 μm (70% of the total soil < 1 mm)	Apollo 12 Average of 12001,84 and 12070,139 20–1000 μm (75% of the total soil < 1 mm)
Basalt	4	9
Anorthosite	0.3	1
Breccia	~ 7	~ 8
Agglomerates	39 (Agglomerates + Glass fragments)	46 (Agglomerates + Glass fragments)
Glass fragments		
Regular glass bodies	1.5	0.7
Pyroxene + olivine	29	25
Plagioclase	14	7
Opaques	4	3
Pyroxene/plagioclase	2.0	3.6

Table 9. Normative composition of Apollo 11 and Apollo 12 soils (CIPW—norms).

	Apollo 11 10084*	Apollo 12 12070**
Q	0.00	0.00
Or	0.83	1.31
Ab	3.81	3.91
An	35.33	33.15
Di	19.31	13.85
En	12.69	14.70
Fs	10.97	14.87
Ol	2.47	11.70
Il	14.24	5.47
Ap	0.23	0.75
Pyroxene + Olivine / Plagioclase	1.13	1.44

* Average chemical composition compiled by COMPSTON *et al.* (1970).

** Average of chemical analyses by LSPET (1970), ANNELL *et al.* (1971), and ROSE *et al.* (1971).

lateral flow of disintegrated weakly shocked material. The constituents of type (1a) and (1b) breccias will originate mainly from the basement rocks and only subordinately from the regolith.

Breccia 12034 and similar breccia fragments in soil 12033 may be suevite-like breccias (1a) (QUAIDE *et al.*, 1971). Because of their unique composition and the location of the Apollo 12 site within ray systems of large craters excavated in the Fra Mauro formation these breccias are assumed to originate from an impact into this formation (e.g., LSPET, 1970). Breccias of the type (1b) have not been identified with sufficient certainty. Monomict anorthositic breccias rarely observed at both landing sites and discussed by WOOD *et al.* (1971) may perhaps belong to this type.

In the case of small impacts (2), shock compression will predominantly affect the regolith which, as a porous medium, reacts in a quite different way than nonporous rocks such as most lunar basalts. According to known Hugoniot data, distinctly more irreversible heat is produced by a particular shock pressure in porous materials than in nonporous media (see e.g. AHRENS and GREGSON, 1964). Consequently, in the loose regolith thermal effects will predominate over deformational shock effects.

Observations on shocked Coconino sandstone, Meteor Crater (KIEFFER, 1970), and results of recovery shock experiments (SHORT, 1968) provide some informations about progressive shock metamorphism of porous material which may be applied to the regolith. An impact into the regolith produces zones of decreasing pressure and temperature. Upon excavation the individual zones yield various mixtures of melt and solid fragments which, by quenching, consolidate as breccias. The following types of shocked regolith, produced by "small" impacts, listed with decreasing shock temperature are to be expected: (2a) highly vesiculated glass penetrating and bonding less shocked soil material; (2b) soil bonded by a vesiculated glassy matrix, formed in situ by local melting along grain boundaries and by softening or welding preexisting glass particles; (2c) soil bonded by a dense fine glass matrix formed by small scale melting along the walls of collapsed pores and by softening and welding preexisting glass particles; and (2d) soil compacted by shock compression to a dense but friable aggregate without melting along pore walls. It is to be expected that mineral fragments in breccias of types (2b) and (2c) will display only minor shock effects, such as planar deformation structures. Diaplectic glass will be subordinate or missing.

The preliminary study of more than 100 breccia fragments, mainly selected from soil samples, has shown that it should be possible to arrange them in the sequence (2a)–(2d) by a very careful microscopic investigation. Part of the particles called glassy agglomerates may belong to type (2a) of the sequence. They should differ from agglomerates formed by melt splashes on the soil surface by their content of shocked mineral and rock fragments.

Another type of breccia (2e) produced by impacts affecting only the regolith may be formed at the beginning of the excavation by lateral flow of weakly shocked material mixed with hot gases from vaporized rocks. Breccias characterized by higher porosity, the preservation of delicate, fragile and vesiculated glass particles, accretionary lapilli and a strikingly low content of shocked mineral fragments, may be formed in this way as it was suggested by MCKAY *et al.* (1970) and WATERS *et al.* (1971).

Table 10. Modal composition of breccias (vol. %).

	Apollo 11					Apollo 12	
	M62	10085,26 M56	M54	10027,11 M55	Average	12010,4	12034,11
Matrix	35	31	27	50	36	25	23
Without matrix							
Basalt	17	13	29	24	21	37	6
Anorthosite	3	5	1	2	3	5	3
Breccia	—	—	2	—	0.5	—	1
Glass	33	29	35	26	31	20	54[1]
Regular glass bodies	1	1	4	2	2	< 1	< 1
Pyroxene + Olivine	27	30	11	24	23	27	20
Plagioclase	8	10	9	13	10	5	10
Opaques	11	7	8	8	8	4	5
Pyroxene/plagioclase	3.4	3.0	1.2	1.8	2.3	5.4	2.0

[1] Including 6% vitrophyric basalt (volcanic glass).

amount of rocks in breccias is probably due to the abundance of rock fragments in coarser fractions. The apparent higher value of the pyroxene/plagioclase ratio may, at least in part, be caused by the camouflage of small plagioclase particles in the matrix.

Breccia 12010 from the outer rim of Middle Crescent Crater differs from soils 12001 and 12070, collected 200 m away from the crater rim, by a higher amount of basalt and pyroxene fragments which may originate from an admixture of pyroxene rich basaltic rocks excavated by the Crescent Crater event. Soil (12034,74) and breccia (12034,11) from Head Crater have closely related compositions characterized by abundant maroon-brown "KREEP"-glasses. The soil contains fragments of the 12034 breccia type.

Careful microscopic thin section studies of large and small breccia fragments showed, that among the various breccias of both landing sites certain textural differences exist. We found that the following properties could be meaningful for classification and genesis of breccias: (1) matrix porosity, (2) amount of glass in the matrix, (3) texture of the matrix glass, (4) amount of shocked rock and mineral fragments, (5) presence or absence of delicate and fragile glassy agglomerates, (6) degree of compositional variation of glass fragments and regular bodies, and (7) glass coating of breccia fragments and its textural relationship to the matrix glass.

Because gradational transitions exist between all types which could be established according to these aspects, the attempt to classify the breccias should not only be based on petrographic observation but also on a tentative genetical model of the different formation processes of impact breccias under lunar conditions.

In a rather simplified approach, we distinguish between (1) large impacts penetrating deeply into the basement and (2) smaller impacts affecting only the regolith layer. In the case of large impacts, we have to expect (1a) suevite-like breccias with a high content of shocked rocks in all stages of shock metamorphism, including shock-fused glasses; and (1b) impact breccias with a low content, if any, of fused glasses and a low amount of shocked material. The latter breccia type which probably has a terrestrial analogue in the Bunte Breccie of the Ries ejecta blanket, would form by a

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